1.3 Laws of flotation

1.3.1 Archimedes' principle

Archimedes' principle states that, when a body is wholly or partially immersed in a liquid, it experiences an upthrust (apparent loss of mass) that is equal to the mass of liquid displaced.

The upthrust creating the apparent loss of mass is termed 'buoyancy force' (Bf).

Consider a block of steel measuring 2 m × 2 m × 2 m that has a density of 7.840 t/m^3.

Example 6 (a)

If the block were to be suspended by a ship's crane that has a very accurate load gauge, what mass would register on the gauge if the block were suspended over the ship's side in air?

Solution

Since: Mass = Volume × Density

Mass of the block = (2 m × 2 m × 2 m) × 7.840 t/m^3 = **62.720 t**

This value would be displayed on the crane driver's gauge.

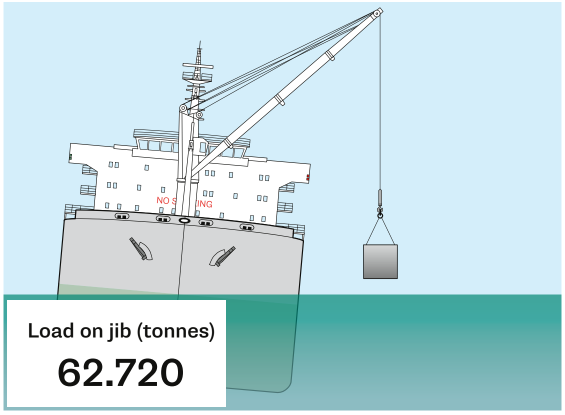


Figure 1.6 – Block suspended over the side, clear of the water.

Example 6 (b)

The crane driver now lowers the block so that it becomes half submerged in the dock water, which has a density of 1.020 t/m^3.

What mass will the load gauge now indicate?

Solution

Figure 1.7 shows the block now displacing a volume of water where:

Volume of water displaced = (2 m × 2 m × 1 m) = 4 m^3

∴ Mass of water displaced = volume of water displaced × density of the dock water

= 4 m^3 × 1.020 t/m^3

= 4.080 t, which represents the upthrust due to buoyancy force (Bf) created by the displaced water.

∴

Mass of block	62.720 t
Upthrust due to Bf	4.080 t
Gauge reading	**58.640 t**

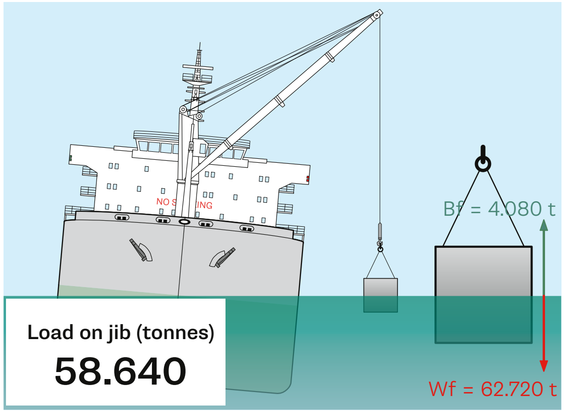


Figure 1.7 – The block is now half-submerged in dock water RD 1.020.

Example 6 (c)

What mass will the load gauge indicate if the crane driver now lowers the block so that it is completely submerged in the dock water?

Solution

Figure 1.8 shows the block now displacing a volume of water where:

Volume of water displaced = (2 m × 2 m × 2 m) = 8 m³

∴ Mass of water displaced = volume of water displaced × density of the dock water

= 8 m³ × 1.020 t/m³

= 8.160 t, which represents the upthrust of the buoyancy force (Bf) created by the displaced water.

∴	**Mass of block**	**62.720 t**
	Upthrust due to Bf	**8.160 t**
	Gauge reading	**54.560 t**

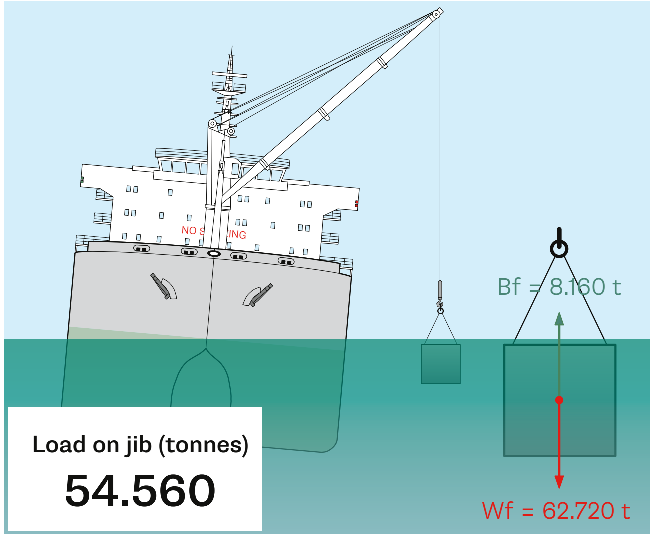


Figure 1.8 – The block is now totally submerged in dock water RD 1.020.

1.3.2 Law of flotation

This law states that every floating body displaces its own mass of the liquid in which it floats.

The displacement of a ship, or any floating object, is defined as being the number of tonnes of water it displaces. It is usual to consider a ship displacing salt water of density 1.025 t/m³. However, fresh water values of displacement (1.000 t/m³) are often quoted in a ship's hydrostatic data.

The volume of displacement is the underwater volume of a ship afloat, ie the volume of the hull below the waterline.

To calculate the displacement (W) of a ship, the following needs to be known:

- The volume of displacement (V)
- the density of the water in which the ship floats (ρ).

Since: Mass = Volume × Density

the mass, or displacement, of a ship is given by:

Displacement = Volume of displacement × Water density

ie **$W = V \times \rho$**

1.3.3 Draught and freeboard

Draught is the vertical distance from the keel to the waterline as measured at points of interest along the ship's length, usually forward, aft and amidships. (More precisely, the draught readings are taken as those read at the forward and aft perpendiculars and amidships. These terms are defined in Section 1.6.)

Draught is expressed in metres. If the draughts forward and aft are the same, the ship is said to be on an even keel.

Freeboard is usually taken as being the vertical distance between the waterline and the top of the uppermost continuous deck at amidships. It is expressed in millimetres.

Hull depth = Draught + Freeboard

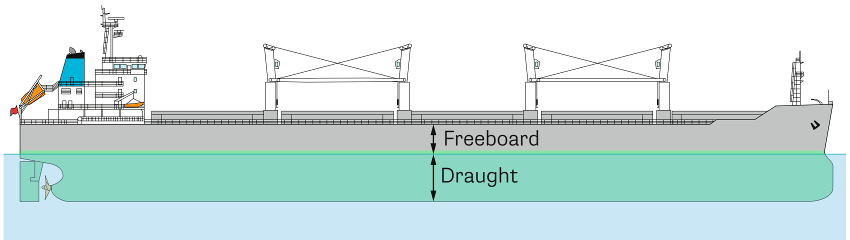


Figure 1.9 – Draught and freeboard.

1.3.4 Reserve buoyancy

Reserve buoyancy is the volume of the enclosed spaces above the waterline, usually considered up to the height of the uppermost continuous deck, termed the freeboard deck on a cargo ship. Superstructure may also be considered as reserve buoyancy. Reserve buoyancy is a very important factor in determining a ship's seaworthiness, so minimum freeboards are assigned to a ship to ensure that there is adequate reserve buoyancy at all times.

1.3.5 Submarines

To further understand the application of Archimedes' principle and the law of flotation, it is worth considering how a submarine dives and surfaces (see Figure 1.10).

When a submarine is floating on the surface, it displaces a mass of the water in which it floats that is equal to the mass of the submarine. In this condition, the submarine has positive buoyancy. Unlike a ship, a submarine can vary its buoyancy to allow it to sink by using the effect of negative buoyancy, or to level off at a certain depth by using the effect of neutral buoyancy.

To control buoyancy, a submarine uses ballast and trim tanks that can be filled with either ballast water or air.

When floating on the surface, the ballast tanks are partly filled with ballast. The submarine has positive buoyancy and so conforms to the law of flotation whereby the overall density of the submarine is less than the density of the water in which it floats.

To dive, the ballast tanks are filled with water and the air is vented out, creating negative buoyancy. The overall density of the submarine is now greater than the surrounding water, causing it to sink. It now conforms to Archimedes' principle.

To level off at the required depth, the excess of ballast water is forced out by compressed air until the overall density of the submarine equals that of the density of the surrounding water and a state of neutral buoyancy is achieved.

A submarine uses trim tanks to control buoyancy and trim. The forward trim tank may be used to shorten dive time and to get clear of the surface quickly. Hydroplanes at the stern are used to control the dive angle and assist manoeuvrability. When the submarine reaches its cruising depth, the hydroplanes are adjusted so that the submarine moves level through the water and ballast is adjusted to attain a state of neutral buoyancy.

To surface, compressed air from the compressed air flasks is forced into the ballast tanks and the ballast water is forced out of the submarine until its overall density is less than the surrounding water (positive buoyancy) and the submarine rises. The hydroplanes are angled to increase surfacing speed. In an emergency, the ballast tanks can be filled quickly with high-pressure air to blow out the ballast water to take the submarine to the surface very rapidly.

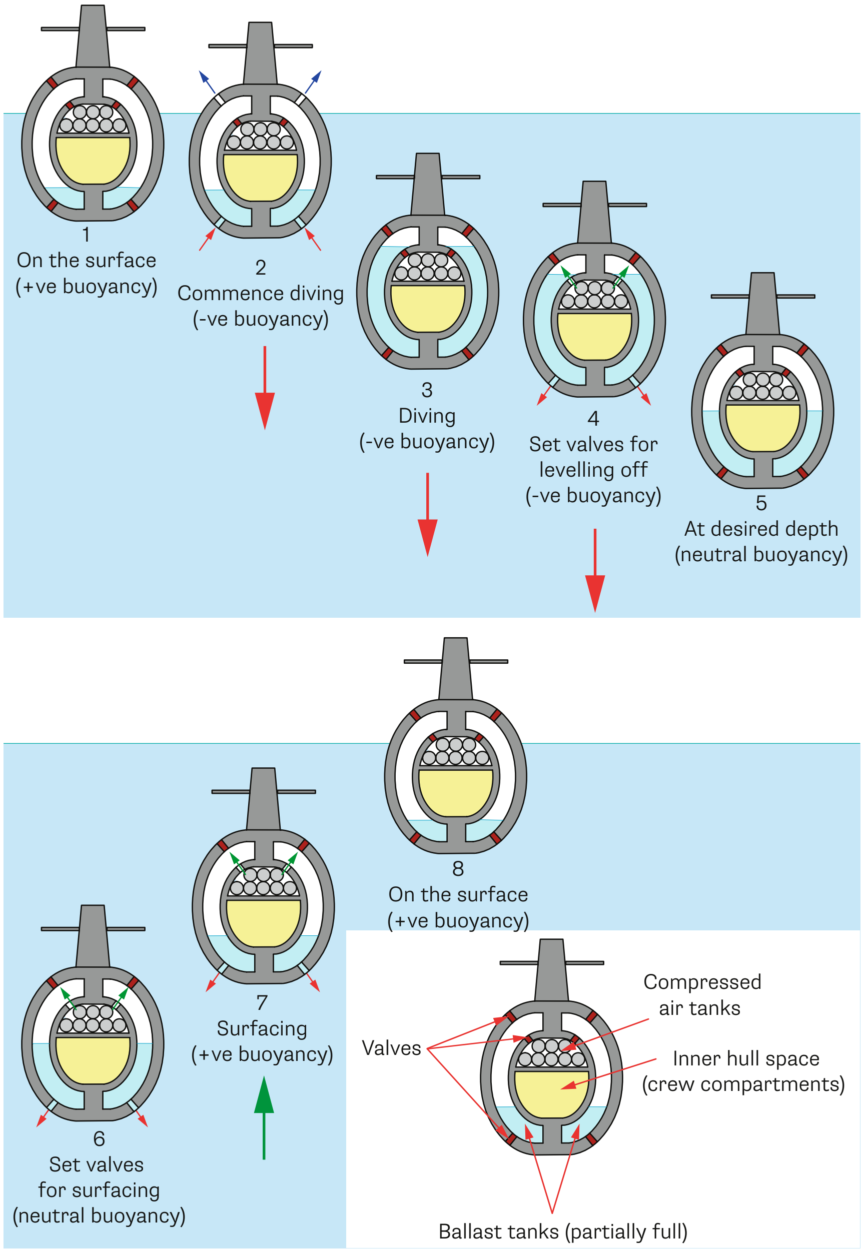


Figure 1.10 – Archimedes' principle as applicable to submarines.

1.4 Simple box-shaped vessel calculations

To enforce understanding of the laws of flotation, it is convenient to consider box-shaped vessels floating on an even keel. The volume of displacement of a box-shaped vessel is easy to calculate.

1.4.1 Calculating the displacement of a box-shaped vessel

Consider the box-shaped vessel in Figure 1.11.

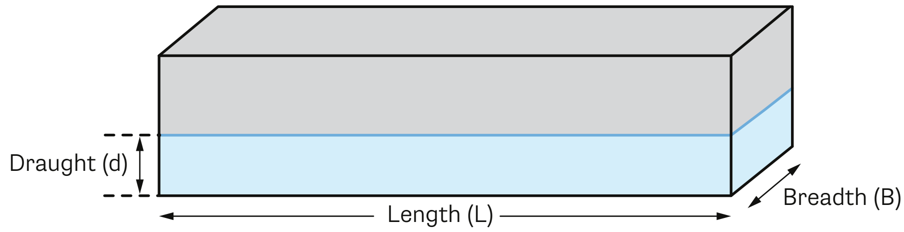


Figure 1.11 – Box-shaped vessel underwater displacement dimensions (even keel assumed).

Mass = Volume × Density

ie Displacement = Volume of displacement × Water density

where: Volume of displacement (box-shaped vessel) = Length × Breadth × Draught

$(V = L \times B \times d)$

Therefore: $\textbf{Displacement}_{BOX} = (L \times B \times d) \times \rho$

or: $W_{BOX} = (L \times B \times d) \times \rho$

Example 7 (a)

Calculate the displacement of a box-shaped vessel that has length 80.0 m, breadth 16.0 m and floats at a draught of 4.2 m in salt water (density 1.025 t/m³).

Solution

$W_{BOX} = (L \times B \times d) \times \rho$

$\therefore \quad W_{BOX} = (80.0 \times 16.0 \times 4.2) \times 1.025$

$\therefore \quad W_{BOX} = \mathbf{5510.4\ t}$

Consider what happens to the same box-shaped vessel if it is now towed into water having lesser density, say 1.006 t/m³.

If the formula: Displacement = Volume of displacement × Water density

is considered, the water density has decreased. Since the displacement has not changed, the volume of displacement must increase in order that the displacement remains constant.

Therefore, the box-shaped vessel will sink a little, ie the draught will increase.

Example 7 (b)

Calculate the draught of the box-shaped vessel in Q. 7 (a) if it is now floating in water of density 1.006 t/m³.

Solution

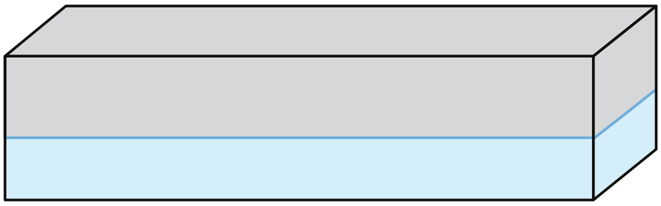
$W_{BOX} = (L \times B \times d) \times \rho$

$\therefore \quad 5510.4 = (80.0 \times 16.0 \times d) \times 1.006$

$$\therefore \quad d = \frac{5510.4}{(80.0 \times 16.0 \times 1.006)}$$

$\therefore \quad d = \mathbf{4.279\ m}$

Note that the increase in draught is: 4.279 m
-4.200 m
0.079 m (7.9 cm or 79 mm. See Figure 1.12)


Displacement 5510.4 t in SW (RD 1.025)

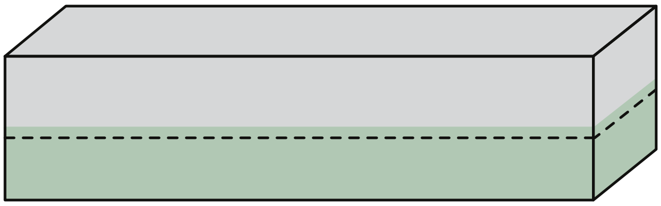

Displacement 5510.4 t in water RD 1.006
(draught increased by 0.079 m in the less dense water)

Figure 1.12 – Draught increases as water density reduces.

- If a ship moves into less dense water, the draught (and volume of displacement) will increase
- if a ship moves into greater density water, the draught (and volume of displacement) will decrease.

Example 8 (a)

A box-shaped barge has the following particulars:

Length 58.0 m   Breadth 14.6 m   Depth 12.4 m

The minimum operational freeboard in salt water is 2280 mm.

Calculate the light displacement of the barge if the draught in the light condition is 3.62 m in salt water.

Solution

$W_{BOX} = (L \times B \times d) \times \rho$

$\therefore \quad W_{BOX} = (58.0 \times 14.6 \times 3.62) \times 1.025$

$\therefore \quad W_{BOX} = \mathbf{3142.1\ t}$

Example 8 (b)

The barge in Q. 8 (a) is towed up river to a berth where the water density is 1.008 t/m³. Calculate the draught of the barge on arrival at the berth.

Solution

$W_{BOX} = (L \times B \times d) \times \rho$

$\therefore \quad 3142.1 = (58.0 \times 14.6 \times d) \times 1.008$

$$\therefore \quad d = \frac{3142.1}{(58.0 \times 14.6 \times 1.008)}$$

$\therefore \quad d = \mathbf{3.681\ m}$

Example 8 (c)

4860 tonnes of cargo is loaded while the barge is alongside. Calculate the final draught (assuming that the barge remains upright and on an even keel).

Solution

Initial (light) displacement	3142.1 t
Cargo loaded	4860.0 t
Final displacement	8002.1 t

$W_{BOX} = (L \times B \times d) \times \rho$

$\therefore \quad 8002.1 = (58.0 \times 14.6 \times d) \times 1.008$

$$\therefore \quad d = \frac{8002.1}{(58.0 \times 14.6 \times 1.008)}$$

$\therefore \quad d = \mathbf{9.375\ m}$